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POOL BOILING OF WATER FROM
MECHANICALLY POLISHED AND
CHEMICALLY ETCHED STAINLESS STEEL SURFACES

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ABSTRACT

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Nucleate boiling heat transfer from mechanically polished and chemically etched surfaces is presented. The use of the Rohsenow Equation is discussed. It is shown that the Rohsenow Equation may be used if suitable adjustment of the coefficient C_{sf} and the exponents are made.

Characterization of the boiling surface is an important aspect of boiling heat transfer. Surface roughness as measured by root mean square in micro-inches is recommended in conjunction with a designation of the surface-fluid combination and surface preparation. The present investigation is concerned with pool boiling water from stainless steel heating strips. Two preparation techniques have been used -- mechanical polishing and chemical etching. The etching solutions were ferric chloride and hydrochloric acid. It is noted that the effect on boiling as is influenced by the surface characteristic is different depending on the etching solution and the etching time.

A comparison is made of the data for all methods of surface preparation. The significance of the methods developed for predicting boiling heat transfer for design purposes is pointed out.

Author

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NOMENCLATURE

A. Letter Symbols

<u>Symbols</u>		<u>Dimensional Units</u>
A	Area	ft ²
C _l	Heat capacity liquid	Btu/lb _m °F
C _{sf}	Coefficient in Eq. (1)	dimensionless
g	Acceleration due to gravity	ft/sec ²
g _c	Gravitational constant	lb _m ft/lb _f sec ²
h _{l_v}	Latent heat of vaporization	Btu/lb _m
k _l	Thermal conductivity of liquid	Btu/hr ft °F
q	Heat flow rate	Btu/hr
q"	Heat flux	Btu/hr ft ²
r	Exponent in Eq. (1)	dimensionless
rms	Root mean square	micro-inch
T	Temperature	°F
T _w	Wall Temperature	°F
T _s	Saturation Temperature	°F

B. Greek Letters

Δ	Denotes difference in quantity	
μ _l	Viscosity of liquid	lb _m /ft hr
ρ _l	Density of liquid	lb _m /ft ³
ρ _v	Density of vapor	lb _m /ft ³
σ	Surface tension	lb _f /ft

C. Specimen - Run Designation

Example .

10 B

Specimen 10
Run B

INTRODUCTION

Heat transfer and pressure drop must be considered in the design of any fluid system subject to a thermal environment. The prediction of boiling heat transfer is of primary importance in the design of nuclear reactors, heat exchangers, and space craft cryogenic systems.

Numerous correlations for nucleate pool boiling have been advanced in the past decade. One of the striking points of many of the equations is they do not interchangeably correlate data from system to system. A reason for the discrepancies which exist is the large number of variables associated with boiling heat transfer. Westwater (1)* points out that 38 dimensionless groups would be obtained for boiling in the general case. Thus, a systematic investigation of the variables involved is necessary to resolve the difficulties associated with boiling heat transfer analysis.

A parameter of great importance is the surface condition or surface-liquid combination. The heat transfer surfaces in many forced and pool boiling experiments have been loosely described or merely indicated by the type of material used. Consequently, data from one system could not be expected to agree with data from another if the surfaces are not exactly the same provided all other parameters are equal. Many experimentalists have tried to compare data and agree that comparison will only be possible when the role of the surface parameter is known.

*Numbers in parentheses indicate References Cited.

This report covers the investigation of pool boiling from two surface-liquid combinations for 304 stainless steel and distilled water. Mechanical polishing and chemical etching of the stainless steel surfaces were selected from a number of possible preparation techniques as recommended by Westwater (2). It was hoped that the study on variations in nucleation sites produced by the two techniques would elucidate the role of the surface parameter in pool boiling. Type 304 bright cold-rolled annealed stainless steel sheet was chosen as the boiling heat transfer surface for the following reasons:

- (1). This type of material is employed in operational heat exchanger equipment
- (2). It is employed in "space age" equipment such as the Saturn Vehicle fuel tanks.
- (3). The current published data contains a limited amount of information on pool boiling heat transfer rates using this material.
- (4). The physical properties for the material retard or prevent corrosion by most fluids used as heat transfer media.

The report includes (A) a brief discussion of previously related work on surface effects on pool boiling. (B) the techniques used to polish and etch the surfaces (C) a presentation of the results of the pool boiling heat transfer tests and a comparison of the data with data available from related studies and (D) possible design criteria for pool boiling.

II. RELATED STUDIES - SURFACE EFFECTS ON POOL BOILING

The significance of any study or collection of data is enhanced by a brief review of the related literature. This chapter provides a synthesis of the pertinent literature and some comments on results on surface effects on boiling heat transfer.

Jakob (3) was one of the first to show that for a given superheat the rate of heat transfer increases with an increase in microscopic surface roughness. No quantitative measurement of this surface condition was made. Others have investigated microscopic roughness more extensively. Surface grain boundaries have been shown to have a negligible effect on boiling by Clark, et al. (4). This disclosure was made in a study of boiling ether and pentane on zinc and aluminum. Active sites ranged from 0.0003-inch to 0.003-inch in diameter.

The work of Corty and Foust (5) is one of the few studies on boiling from polished surfaces. N-pentane, ether and freon were boiled on nickel and copper surfaces prepared with emery paper. The results for surface roughness from 2.2 to 23 rms indicated steeper slopes for the heat transfer coefficient versus superheat than had been found previously. The fact that the authors' slopes were different from those of other investigators illustrates that boiling data are difficult to compare.

A study by Gaertner and Westwater (6) on boiling aqueous nickel salt solutions on copper also showed that as surface roughness increased heat transfer increased.

Griffith and Wallis (7) boiled methanol, ethanol, and water solutions from polished copper. Cavities were pricked into the surface to demonstrate

the increase in heat transfer with an increase in nucleation sites.

A relatively low rms surface roughness has been obtained through a lapping process by Berenson (8). Berenson also polished some copper surfaces for boiling studies with pentane. He was able to achieve variations as high as 600 per cent in the heat transfer coefficient.

Hsu and Schmidt (9) in a study on temperature variations prepared 304 stainless steel heat transfer surfaces by polishing and grinding. Again an increase in heat transfer was noted for an increase in surface roughness.

The literature which has been reviewed here and in Ref. (10) does not clarify completely the role of surface roughness in boiling heat transfer. One important point should be emphasized - the surface preparation technique should be specified as well as the directional character of any rms readings used to describe a boiling heat transfer surface. This point and others are illustrated in the discussion to follow.

Berenson (8) noted the surface preparation technique for his specimens but failed to report the rms characteristic or any other suitable surface characteristic. The author states that observation of the surfaces obviously indicates the rms roughnesses of the emery surfaces are greater than the lapped surfaces or mirror surfaces. His graphs (for copper-pentane) show an interesting result. Heat transfer was greater from the lapped surface than from the emery surfaces, and hence heat transfer decreases with an apparent increase in rms surface roughness. The data of Hsu and Schmidt (9) show a progressive increase in heat transfer with an increase in rms. Hsu and Schmidt "ground" their stainless steel specimens with a B&S surface grinder to attain rms values of 19, 21, and 104 micro-inch. Polishing with an unidirectional motion was used in preparing the

surface with an rms of 5.2 micro-inch. Berenson's lapped surfaces with apparently small rms roughness were circularly lapped while the emery surfaces were stroked in one direction. The primary objective of Hsu and Schmidt was to study temperature variation near the surface as previously mentioned, but they present data on 304 stainless steel and water which are rare.

The necessity of sites has been demonstrated. (11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24) What remains then is: (A) a means of classifying surfaces so that an increase in the classification corresponds to an increase in the number of nucleation sites regardless of surface preparation if possible and (B) an increase in the data on surface-liquid combinations in boiling systems so that correlations similar to that of Rohsenow (25) can be determined. The appropriate equations which are found may then be applied to design problems.

III. PREPARATION AND CHARACTERIZATION OF HEAT TRANSFER SURFACES

A. Preparation of Test Specimens

The available literature on the effect of surface condition on boiling heat transfer indicates that a systematic investigation is necessary before the phenomenon is fully understood and design criteria are established. A careful study of surface effects should include standard methods of surface preparation and a method of accurately measuring the surface topography.

The preparation techniques should result in a number of similarly prepared surfaces with varying degrees of surface roughness. The surfaces must be prepared in an identical manner for any one technique to reduce the possibility of injecting additional variables into the study.

Several methods of producing various surface textures are possible. Some of these methods are chemical deposition or plating, chemical etching, sand blasting, grinding or polishing. Polishing and chemical etching were chosen for this phase of the study on surface effects on pool boiling heat transfer.

The literature reveals that even small changes in the surface texture influence the heat flux versus superheat curve. Accordingly, the emery selected for the mechanical polishing process was of a grit size that would insure a spread of surface texture. The grit sizes used were 600, 400, 320, and 80. A number of test surfaces were prepared for each grit size. Various chemical solutions were used to produce variations in surface roughness for the etched surfaces.

The specimens (4.6" x 1.0" x 0.30") were cut from type 304 cold-rolled bright annealed sheet material. The long dimension was parallel to the rolling direction. Each specimen was examined carefully for any visible scratches and discarded if any were found. Profilometer measurements of seven as received specimens indicated a surface roughness of approximately 4.3 rms, parallel to the mill marks and 4.8 rms perpendicular to the rolling direction. On this basis, it was concluded that the surface texture was essentially independent of the direction in which it was measured for the milled sheet. Details on surface roughness measurements are presented in Section C of this chapter.

Specimens were prepared as follows:

1. Polished Specimens

Seventeen specimens were polished in the direction parallel to the long dimension. Each stroke was counted and applied with a constant pressure parallel to the previous stroke. Extreme care was taken to insure that the specimen was always polished in the same direction. After each 200 strokes the emery cloth was replaced and the specimen examined for consistency. If the specimen was found to have scratches not parallel to the direction of polish, another 200 strokes were applied in an attempt to remove the inconsistency. If, at the end of the additional 200 strokes, the scratch remained, the specimen was discarded.

After polishing the specimens were washed with distilled water to remove any foreign particles. Masking tape was applied to the prepared surface to prevent further scratching. The masking tape was removed, the specimen washed with acetone, rinsed with distilled water and air dried before each profilometer measurement. Table I

presents the various rms values for each specimen. It is seen that some variation in rms surface roughness results even though the same preparation techniques is used. Thus, the specimens are grouped according to rms values.

2. Etched Specimens

Seven specimens were immersed in various chemical solutions to produce variations in nucleation site density. Table II gives the details on surface preparation as well as rms surface characterization for each specimen. No surfaces were used that had visible scratches prior to etching.

B. Methods of Measuring Surface Roughness

Several methods of characterizing surface roughness have been examined. These methods included measurement of rms values using a Profilometer and measurement of cavity spacing and depth using a Proficorder. Other methods of studying surfaces include shadow-graph techniques, optical examination and film replica. However, information obtained by the latter methods is more subjective and therefore not as useful in correlating surface condition with data on boiling heat transfer. Thus, the Profilometer or Proficorder afford two means of describing surface condition.

A brief comment on each instrument should be made to establish the parameter to be used in characterizing pool boiling heat transfer surfaces. The Linear Proficorder is an instrument designed to measure cavity spacing and depth within an accuracy of 0.000001 of an inch. The Linear Profilometer is used to measure the root mean square average deviation from center line of surface topography. The center line is defined as the line about which roughness is measured. The line is parallel to the

general direction of the surface contour such that the sums of the areas contained between it and those parts of the profile which lie on each side of it are equal.

The Profilometer was chosen to characterize the surfaces used in the present investigation. The Profilometer is an instrument of the type widely used in industry, and it provides a standard to which any surface may be compared. The instrument represents surface irregularities in terms of a graph of irregularity height or depth versus surface length.

C. Roughness Measurements

A Physics Research Company Model 15 Profilometer was used to measure surface roughness in rms. The Profilometer was calibrated using a standard provided by the manufacturer. The instrument consistently agreed with calibration data available.

Surface measurements on all specimens were made in both longitudinal and transverse directions. The transverse measurements were made along lines dividing the specimen into four equal parts. Longitudinal measurements were made along the center line. Several randomly selected (as received from the mill) specimens were examined prior to surface preparation. The difference between transverse and longitudinal rms measurement was on the order of 10%. It was assumed that the mill specimens did not exhibit pronounced surface directional characteristics prior to polishing or etching, as previously mentioned.

Subsequent to the mechanical polishing, the surface exhibited a marked change in rms surface roughness in regard to the direction of surface measurement. The chemically etched surfaces were uniform in all directions within 10%.

The rms surface roughness on all the prepared specimens were determined before they were used to obtain heat transfer data. Some specimens which were discolored due to heating effects in approaching burnout were not used to establish reproducibility of the data. These surfaces exhibited changes in surface characteristics due to heating effects as the heat flux approached the maximum point of inflection on a standard boiling curve.

As was noted, directional rms surface character was obtained with the polished surfaces. Previous investigations using rms as a parameter (5), (8), (9), and (11) have not included directional property data. In order to compare experimental results accurately, it is felt that the surface texture should be completely described including any directional properties. A decision must be made, when directional properties exist, as to which rms measurement or measurements should be used as a boiling parameter. The procedure of Corty and Foust (5) in using transverse values of rms as the parameter to characterize the polished surface data was used. The transverse values have the highest variation. The longitudinal values exhibit a slight change. The choice of the transverse rms values does not completely describe the surface unless the surface preparation technique is specified. This will be seen when observing the experimental results for the two surface preparation techniques.

IV. EXPERIMENTAL PROCEDURE

A. Preparation of Boiler and Boiling Surfaces

One of the major parameters that must be considered in a boiling heat transfer experiment is the cleanliness of the test surface and apparatus. The procedure used to clean the apparatus and test section in this study was the same for each experimental run. The apparatus has been described previously (26).

The inside of the boiler was polished with steel wool before each series of runs and washed with distilled water and acetone. The test block assembly was prepared as outlined previously (26). The test specimens were thoroughly cleaned with sodium hydroxide, distilled water and acetone and mounted on the test block assembly. The test assembly was then placed in the boiler for the test. Fig. 1 shows the test specimen positioned in the boiler. Figs. 2 and 3 show overall views of the apparatus.

A vacuum of thirty inches of mercury was applied to the boiler for thirty minutes before the deionized distilled water was admitted. After the filling process was completed, the system was subjected to an additional vacuum of approximately thirty inches for thirty minutes. During the second period of vacuum environment, many bubbles were released from the surface of the boiler and test block assembly. However, at the end of the thirty minutes, very few bubbles were observed to rise to the surface.

The system was exposed to atmospheric pressure and the liquid was brought to a saturation temperature with a preheater upon completion of the degassing process. A minimum of one hour was usually required to

reach saturation temperature. When saturation temperature was reached, the entire system was allowed to reach equilibrium before a test was begun.

B. Test Data

When system equilibrium was reached, power to the test strip was turned on. The system was operated in the boiling mode for thirty minutes at the minimum power setting to allow equilibrium conditions to be obtained before the first data were taken. Power was then increased systematically and the system brought to equilibrium to obtain variation in heat flux data.

Temperatures recorded on a Potentiometer during a test included the three test strip temperatures, the test block temperature, bulk fluid temperature, and the condenser cooling water inlet and outlet temperatures. Details on data reducing can be obtained from Ref. 26. Each set of temperatures was recorded at ten minute intervals with the corresponding values of the voltage and current passing through the test strip. The power was periodically increased by increasing the voltage until a position below the burnout level was obtained. The system did approach burnout, in some cases, thereby damaging the test strip. After the last set of readings were recorded, the power was discontinued to the preheater and test strip; the water was drained from the boiler. The specimens were inspected carefully to insure that water had not penetrated the epoxy used to seal the test strip to the test block assembly.

A total of 40 runs have been conducted on 17 different mechanically polished specimens. The polished specimens were grouped in six categories, according to the transverse rms roughness values. The reason for the

grouping was to obtain a significant range of roughness values to aid in the analysis. Nine runs have been completed using 7 different chemically etched specimens. These specimens have been catalogued in 5 groups.

V. EXPERIMENTAL RESULTS

A. Mechanically Polished Surfaces Pool Boiling Data

A total of 40 runs were conducted on 17 different mechanically polished specimens. The parameter employed to characterize the data is the root mean square (rms) roughness, in micro-inches, as measured by a profilometer transverse to the major dimensions of the specimen. This parameter as stated previously, will be used throughout the discussion of results.

The various data have been arranged in groups according to the roughness value. The average roughness values were used as the significant surface roughness parameter and these are shown in Table I.

All the data are presented in Figs. 4-6 for the six different rms groups. The data are displayed graphically in terms of heat flux versus wall superheat. Letters after specimen numbers refer to runs. Some of the data were reported previously (26,27). However, data for all the specimens were analyzed and displayed collectively.

The data scatter represented in Figs. 4-6 is comparable with that obtained previously by Corty and Foust (5) for n-pentane boiling on a copper surface and Hsu and Schmidt (9) for boiling water on stainless steel. Corty and Foust represented their data as film coefficient versus wall superheat, a method which has since been discouraged by Westwater (1). Corty and Foust attributed part of the scatter to aging of the test specimens. This effect is noticeable in the present data, particularly for specimens 43 and 45, whose roughness is approximately 50 micro-inches, rms. Scatter appears to decrease slightly at higher values of the surface roughness.

A least squares curve fitting procedure considering errors in both ordinate and abscissa was employed in the data correlation. From an inspection of the data, it was determined that the initial few points of each run were different in slope from the data at higher heat fluxes. This indicates that the initial points were for free convection. Data for the free convection and nucleate regimes of boiling can not be correlated by a single expression. Therefore, the free convection regime was not utilized in obtaining the least squares representation of the data as shown in Fig. 4-6. A composite curve of the least squares approximation for the various surface roughness groups is presented in Fig. 7.

A new boiling heat transfer correlation equation was not developed. The equation given by Rohsenow (25) was utilized in the correlation of the data. Rohsenow's equation may be written as

$$\frac{C_l(T_w - T_g)}{h_{lv}} = C_{sf} \left[\frac{q''}{\mu_l h_{lv}} \sqrt{\frac{g_c \sigma}{g(\rho_l - \rho_v)}} \right]^r \left[\frac{C_l \mu_l}{k_l} \right]^s \quad (1)$$

where $r = 0.33$ and $s = 1.7$.

At this point, it is appropriate to discuss the Rohsenow equation and the significance of the exponents of the parameters and the coefficient C_{sf} . The heat flux term exponent establishes the slope of the correlation and is somewhat sensitive to surface contamination. The exponent of the Prandtl number accounts for surface contamination. Rohsenow has stated that the Prandtl exponent can vary from 0.8 to 2.0. No definite guide for estimating an appropriate value in this range is presented. Values of C_{sf} are presented (25,28) for a number of combinations. The Rohsenow

equation correlates the data for these C_{sf} values within acceptable limits. The value of the heat flux exponent used in the correlations cited is the same. This means that all the data for the various liquid surface combinations investigated to data and applied to the equation have had approximately the same slope on a log-log graph of heat flux versus superheat. It means that the slope is fixed and contamination and liquid surface combinations control heat transfer. This is very fortunate. Even if the exact value of the exponent of the Prandtl number is not known, the correlation equation curve can be shifted along the abscissa by the value of the C_{sf} term. This allows one to match the curve and the data when the slopes are nearly the same. Thus, it would appear that the selection of the Rohsenow equation is appropriate for correlating the mechanically polished surface data when the slopes of the data and equation are similar.

Upon comparison of the slopes of the least squares representations of the data and the reciprocal of the heat flux term exponent, it was found that the Rohsenow equation could be used without major adjustments. The values of the exponents of the Prandtl number and heat flux term were not changed. The C_{sf} values used in the equation represent average values for each rms group. These C_{sf} values were obtained by averaging the individual C_{sf} values for each datum combination and surface preparation. Table III presents the C_{sf} values described.

The applicability of the Rohsenow equation to the data cited by Rohsenow (25,28) and other investigations (9) as well as this study on polished surfaces without changing the heat flux term exponent is remarkable. One would be led to believe that the exponent is suitable for all pool boiling data and that the C_{sf} term can be used to account for surface

preparation and surface-liquid combination with a slight variation of the Prandtl exponent. This is not the case as can be seen from Table IV and as will be seen for the chemically etched surface data. Berenson (8), Griffith and Wallis (7), and Gaertner & Westwater (6), present pool boiling data, whose slopes would yield significantly different values for the heat flux term exponent. But this does not destroy the utility of the Rohsenow equation. The equation will correlate data within $\pm 20\%$ with proper values of the coefficient and exponents.

It appears from Figs. 4-6 and the discussion that the Rohsenow equation with the exponents .33 and 1.7 for the heat flux term and Prandtl number respectively and appropriate values of C_{sf} is a valid correlation equation for pool boiling water from polished stainless steel surfaces.

B. Chemically Etched Surfaces Pool Boiling Data

Nine runs have been made with seven chemically etched specimens. Table III describes each specimen and the technique for preparing each surface. As seen from Table III the chemically etched specimens do not have a marked directional rms characteristic. Thus, the surfaces are described by the average of the longitudinal and transverse values of rms.

Again it was decided to use the Rohsenow equation to correlate the data. It is now that what has been said about the heat flux exponent is seen. Figure 8 shows something quite interesting. The slopes of the Rohsenow equation correlations for $r=.33$ are not in close agreement with the slopes of the least squares representations of the data. The exponent of the heat flux term in the Rohsenow equation must be adjusted to bring the curves into agreement within acceptable limits. The value of the exponent for the chemical etched surfaces was obtained by averaging the slopes of the

least squares curve fits for all rms groups and taking the reciprocal of the average. This average exponent was then used in the Rohsenow equation and the equation and data used to determine average C_{sf} values for each rms classification. The Rohsenow equation correlation curves with the adjusted exponent and appropriate average C_{sf} value are seen in Figs. 9-13 and are compared with the least squares curve fits of the data. Fig. 14 shows a composite curve for the chemical etched data in terms of least squares fits.

Just as was the case for the mechanically polished surfaces, it is felt that the Rohsenow equation correlates the data within acceptable limits. Again one must be careful to select the proper exponent for the heat flux term in the equation. It appears that each method of surface preparation affects the heat transfer mechanism and hence slope of the Rohsenow equation. Until this study, this point concerning the Rohsenow equation has been dormant.

C. Comparison of Pool Boiling Data

First it must be emphasized that the study of two surface preparation techniques for water boiling heat transfer from stainless steel has emphasized A) that the exponent of the heat flux term in the Rohsenow equation must be adjusted with respect to the surface preparation technique and B) that the equation is useful for pool boiling correlations where the surfaces have been prepared. A comparison of the two preparation techniques Fig. 15, shows considerable overlap with respect to rms.

What is significant is that the slopes of the least squares fits of the chemically etched boiling data are greater than the slopes of the mechanically polished data. This suggests that chemical etching produces a greater number of nucleating sites. The as received from the mill

specimen data at the extreme right of the graph for the most part indicate that preparing the surfaces improves the heat transfer.

A comparison of data for the two preparation techniques for similar rms groups does not disclose a significant pattern. Additional data are needed for both techniques in each rms group to establish a definite trend in the heat transfer as a function of rms surface roughness.

A study of Fig. 8 suggests a trend for the chemically etched data if both rms and the chemical etchings solution are considered. The specimens etched with FeCl_3 exhibit a steady increase in heat transfer with an increase in surface rms. It is also apparent that the FeCl_3 etching solution does not produce as many nucleation sites for a 32 rms surface as one etched with HCL since the data for a surface prepared with HCL is far to the left of any of the surfaces prepared with FeCl_3 .

VI. SUMMARY AND CONCLUSIONS

The ultimate desirable result of studies on surface effect on boiling is a method of surface characterization which would describe an increase in nucleation sites by an increase in the descriptor index. This may be possible in the future after a number of investigations on the phenomena have been completed. This particular study has accomplished the following:

1. Increased the range of applicability of the Rohsenow equation for pool boiling from stainless steel in contact with water. New values of C_{sf} and the exponent of the heat flux term have been determined.
2. Shown that on the basis of the data collected that surface preparation technique affects the boiling heat transfer mechanism. The slopes of the boiling data for the mechanically polished surfaces are less than those for the chemically etched surfaces on a log-log plot of heat flux versus wall superheat. Both surface preparation techniques increase the heat transfer from stainless steel.
3. Emphasized the statement that rms surface roughness is not adequate in itself to describe a boiling heat transfer surface.
4. Indicated that there may be a trend in heat transfer as a function of rms roughness for the chemically etched surfaces for each chemical etching solution.
5. Shown that there does not appear to be a definite trend in heat transfer as a function of rms roughness for the mechanically polished surfaces.

6. Shown that the exponent of the Rohsenow Equation varies. The exponent of the heat flux term appears to account for surface preparation technique.
7. Shown the desirability of extending the use of the Rohsenow Equation. It is suggested that the equation be applied to cryogenic pool boiling data.

The establishment of design criteria has been limited to stainless steel water systems operating in the nucleate boiling regime. This regime represents the safe region of operation since it does not uncontrollably approach the first maximum heat flux point on the boiling curve. The extension of the information on the heat flux exponent in the Rohsenow Equation and C_{sf} is recommended for other surface preparation techniques as well as other surface liquid combinations. Cryogenic liquids in contact with a stainless steel surface should provide interesting information to establish design criteria and the applicability of the Rohsenow Equation to cryogenic boiling systems.

In conclusion it should be stated that additional data on chemical etched surfaces should be obtained. These data for various rms values for several etching solutions should show if there is a trend in pool boiling data as a function of rms. In addition, it should be emphasized that the Rohsenow Equation reported in 1952 in the ASME literature appears to be a very good correlation equation for pool boiling. The extension of its range of applicability has not been pursued. This study with one liquid surface combination and two techniques for surface preparation has materially advanced the utility of the Rohsenow Equation.

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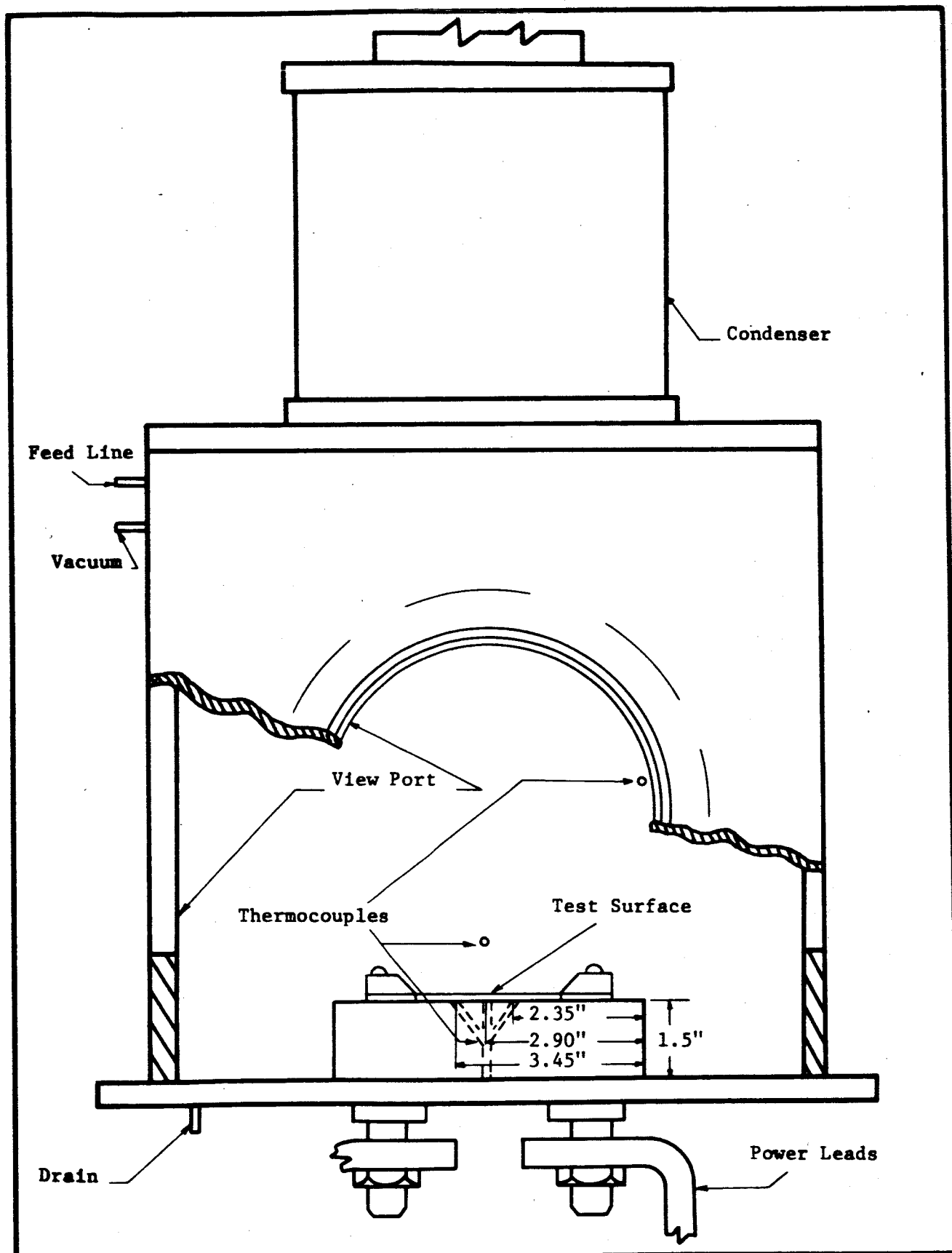


Fig. 1 Side view of Boiler with Test Specimen location

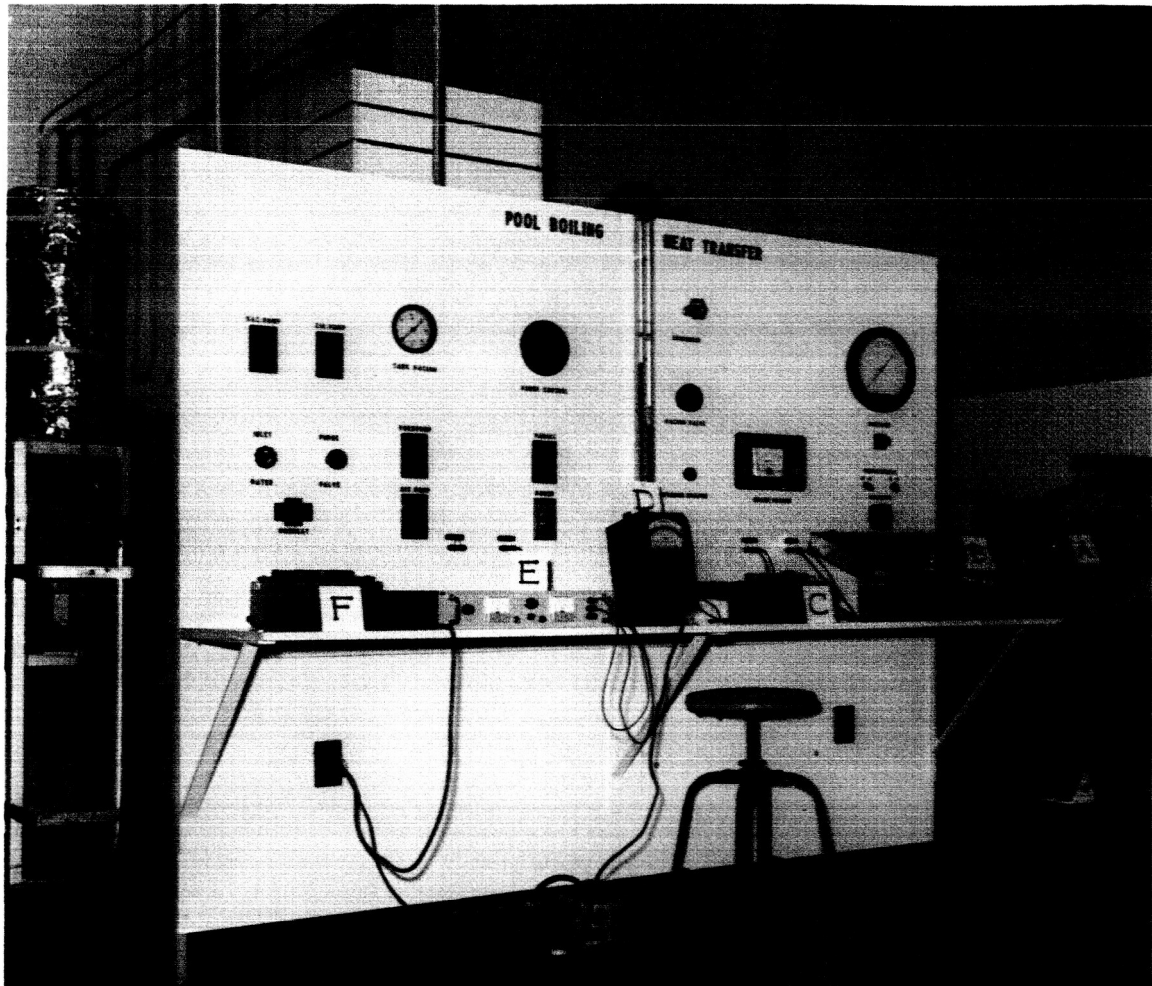


Fig. 2 Front View of Pool Boiling Apparatus

- | | | | |
|---|-------------------------|---|-------------------------|
| A | Visicorder | D | Power Control Voltmeter |
| B | Potentiometer | E | Control Power Supply |
| C | Test Specimen Voltmeter | F | Test Specimen Ammeter |

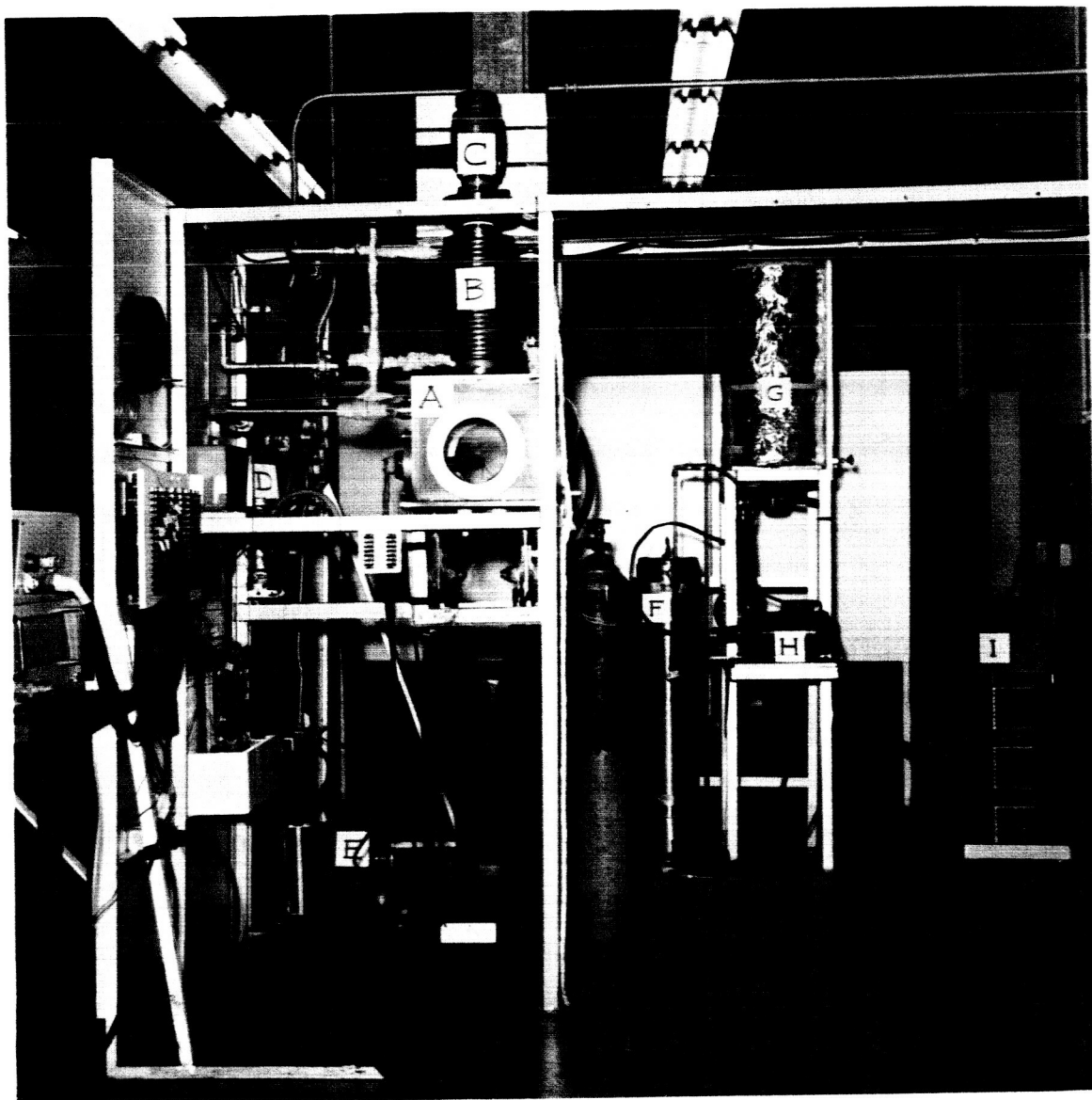


Fig. 3 Side View of Pool Boiling Apparatus

- | | | | |
|---|-------------------|---|------------------|
| A | Boiler | F | Deionizer |
| B | Condenser | G | Supply Tank |
| C | Orifice and Valve | H | Circulation Pump |
| D | Diffusion Pump | I | Power Supply |
| E | Vacuum Pump | | |

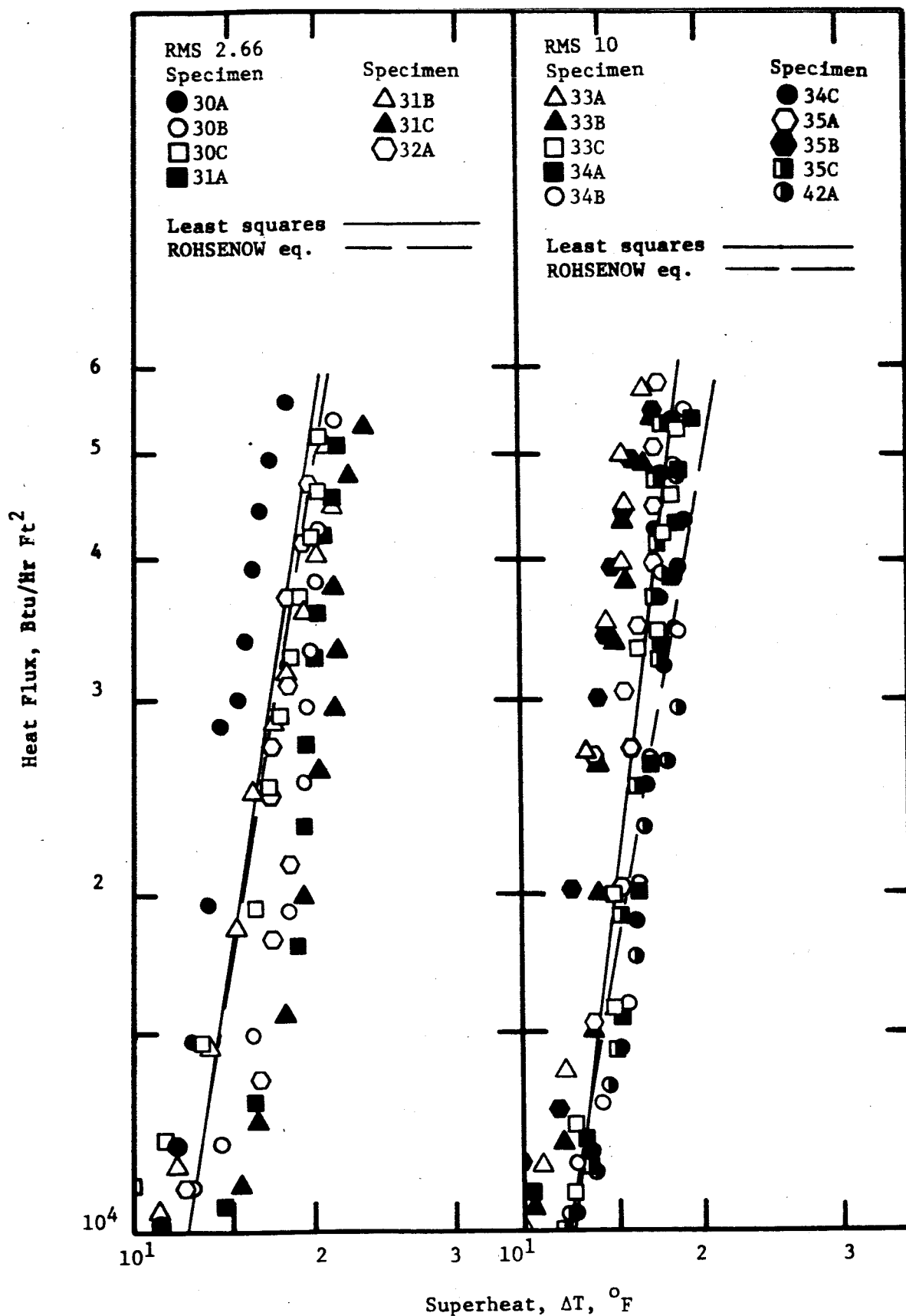


Fig. 4 Heat Flux versus Superheat For Mechanically Polished Surfaces of 2.66 & 10 RMS.

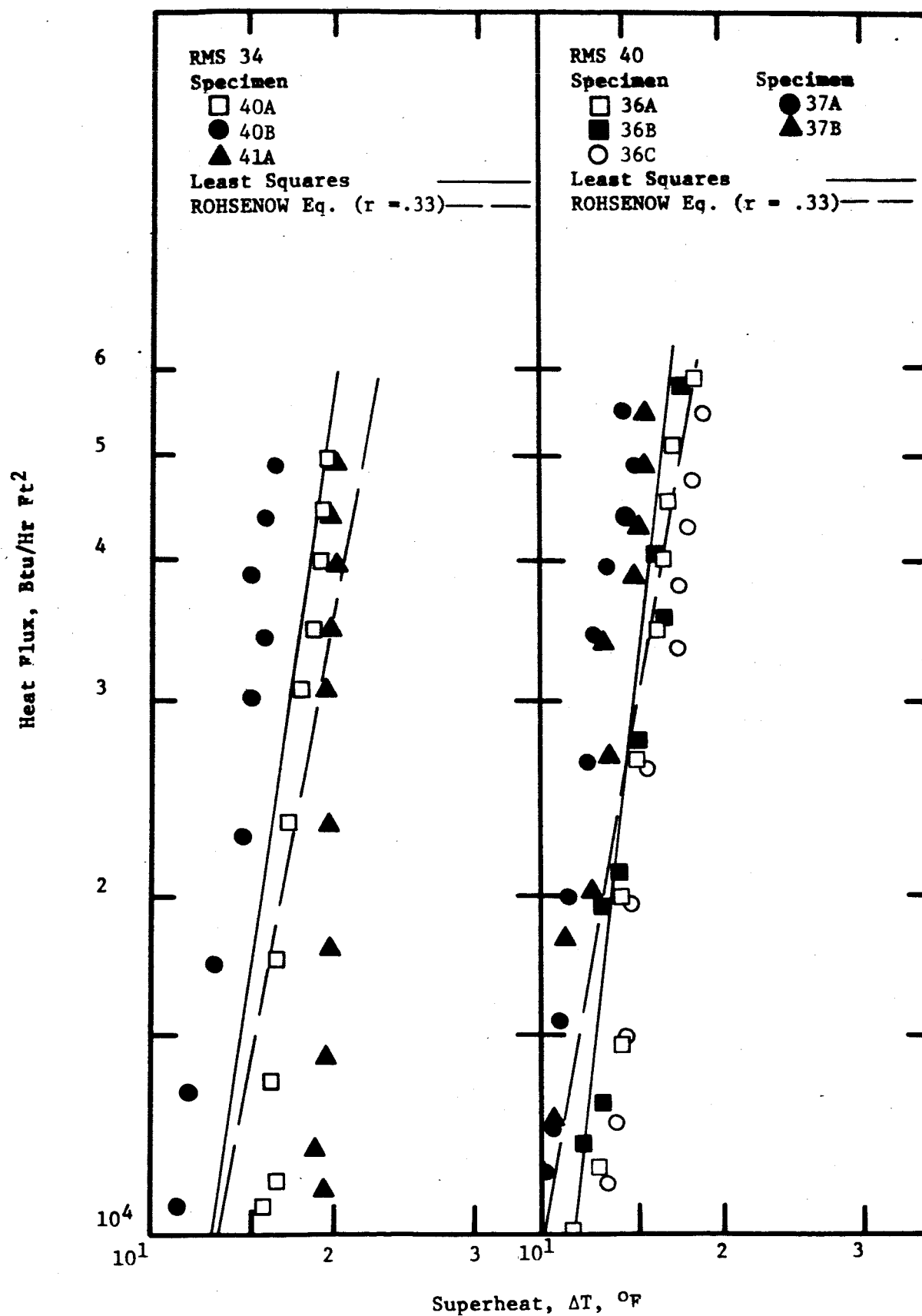


Fig. 5 Heat Flux versus Superheat For Mechanically Polished Surfaces of 34 & 40 RMS.

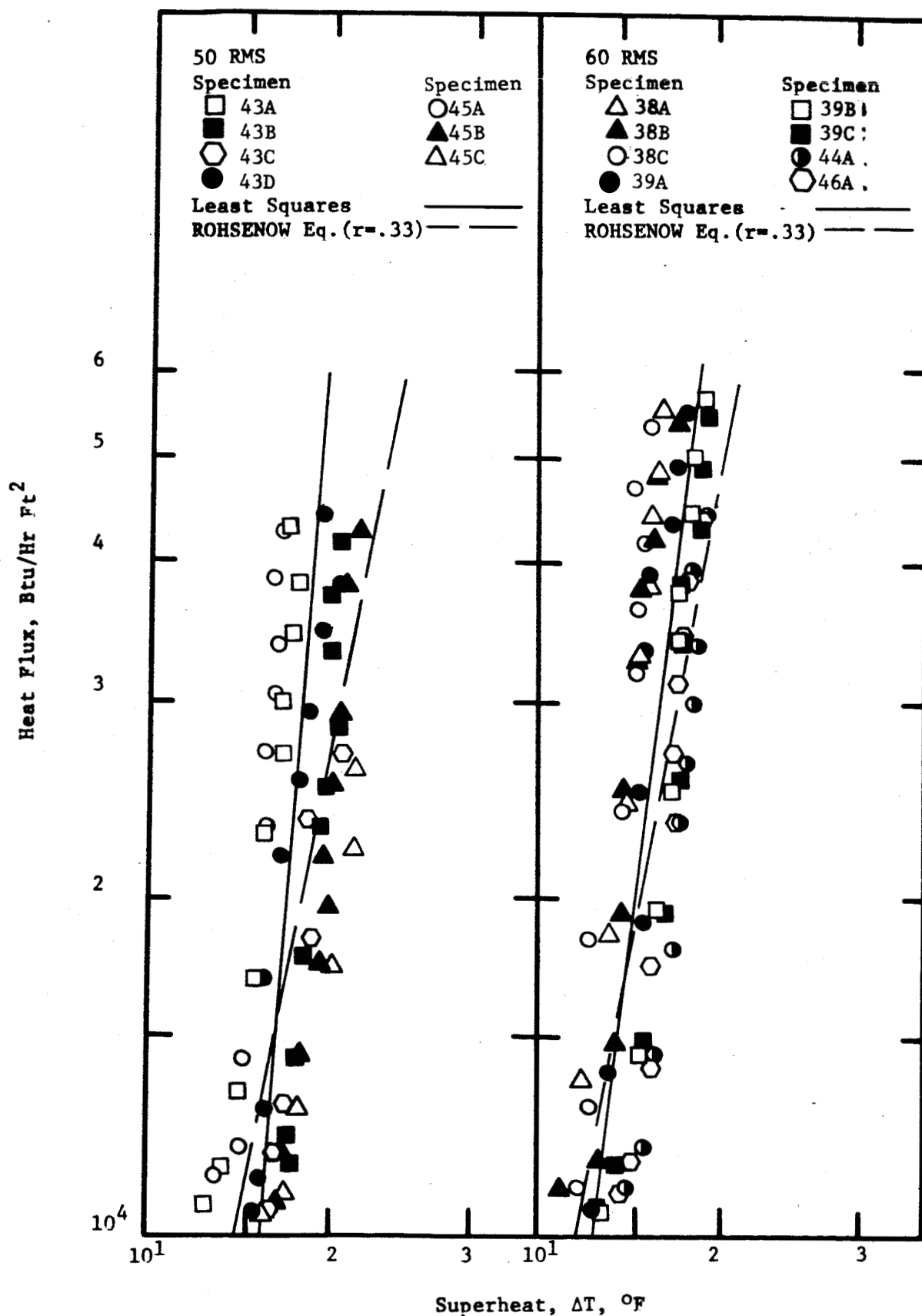


Fig. 6 Heat Flux versus Superheat For Mechanically Polished Surfaces of 50 & 60 RMS.

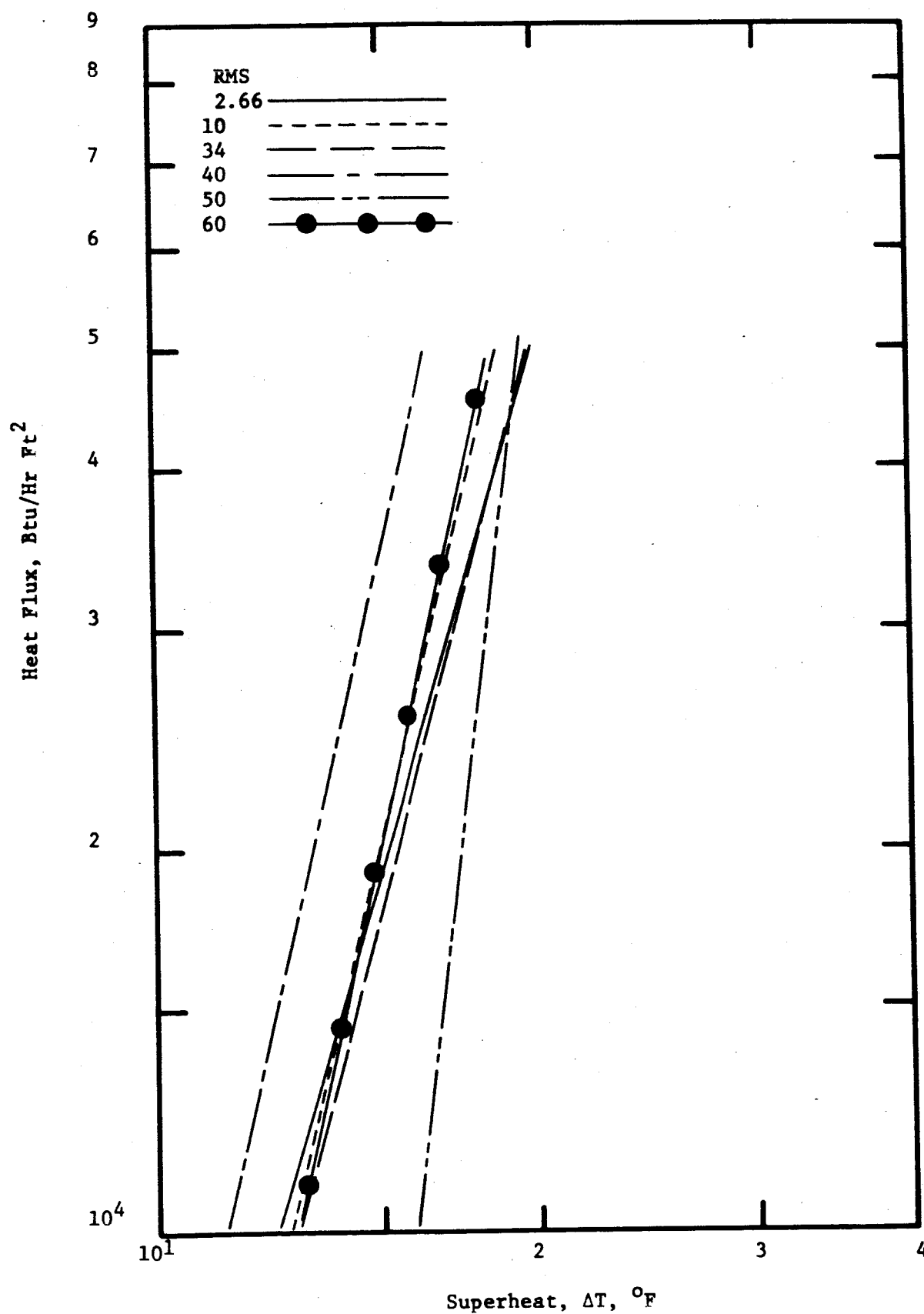


Fig. 7 Composite Heat Flux versus Superheat for Mechanically Polished Surfaces.

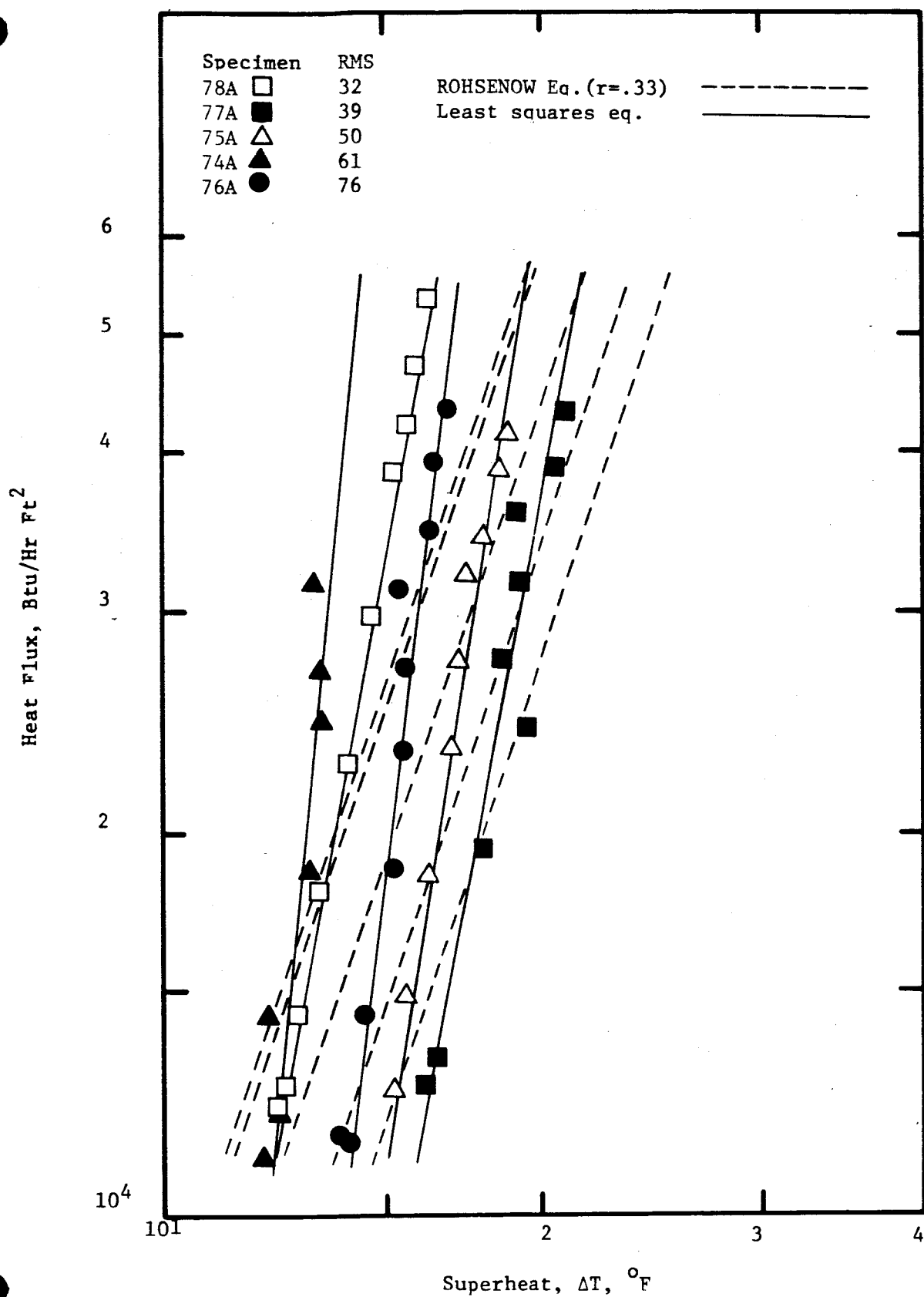


Fig. 8 Composite Heat Flux versus Superheat for Chemically Etched Surfaces. ($r=.33$)

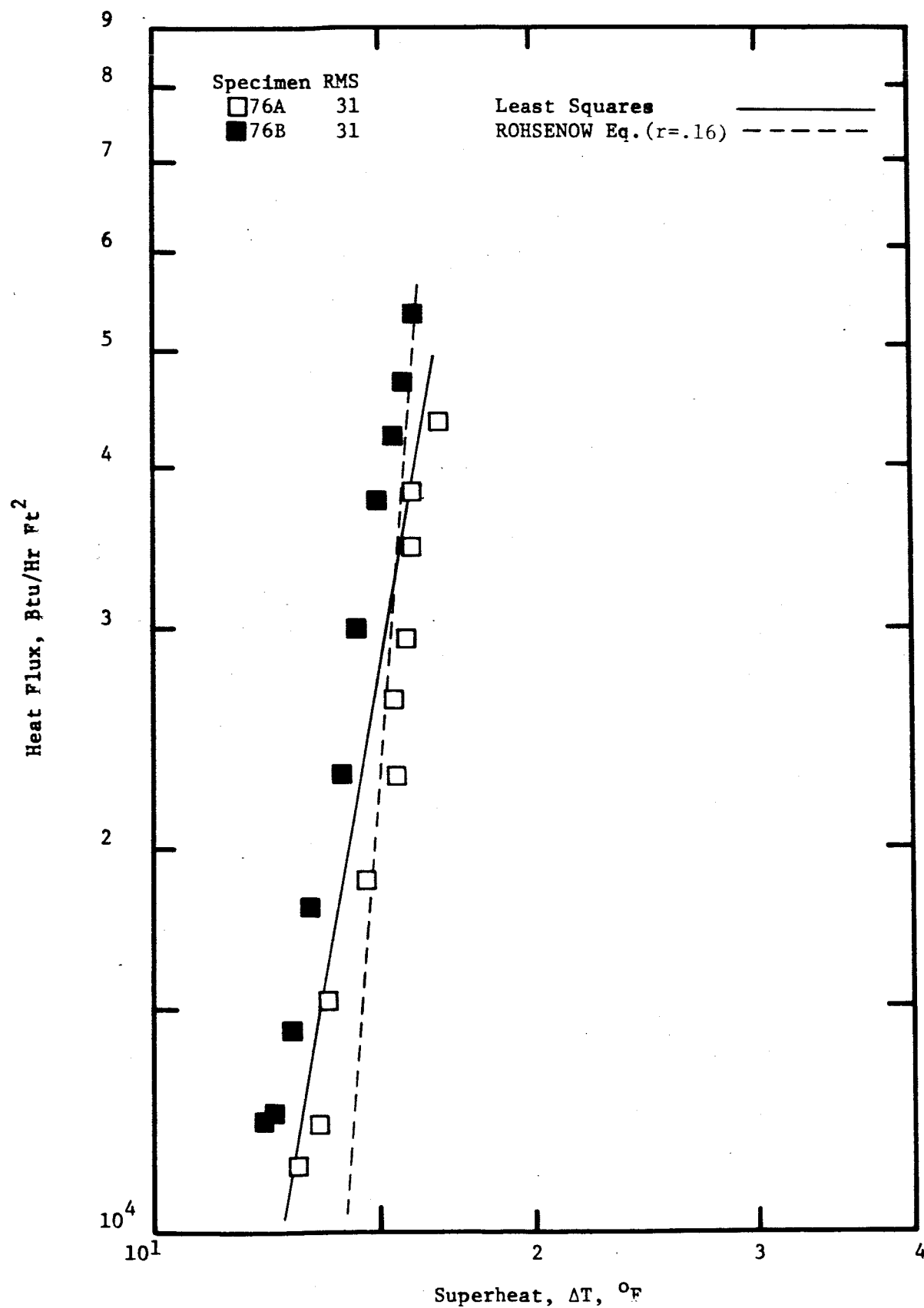


Fig. 9 Heat Flux versus Superheat for Chemically Etched Surfaces of 31 RMS.

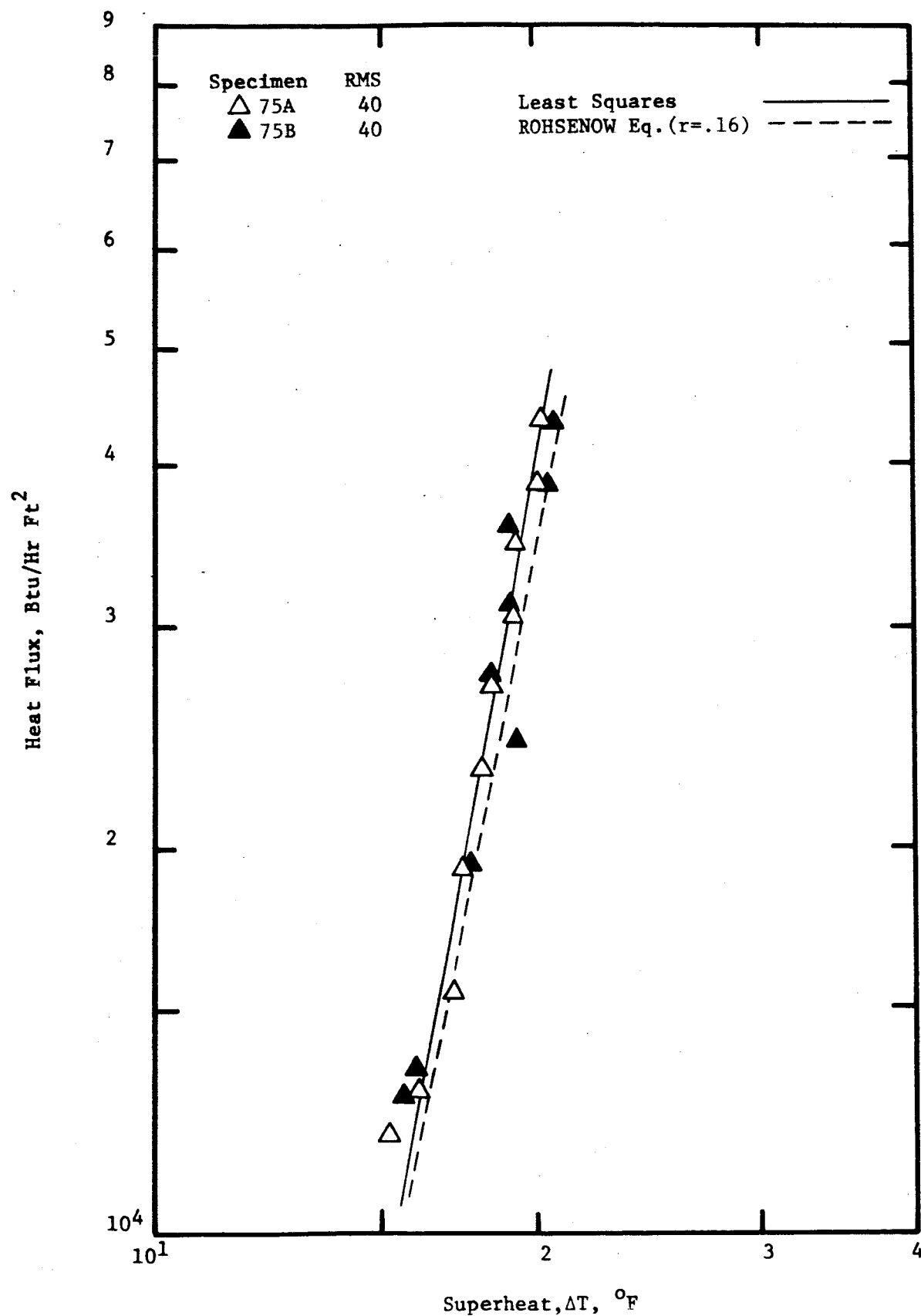


Fig. 10 Heat Flux versus Superheat for Chemically Etched Surfaces of 40 RMS.

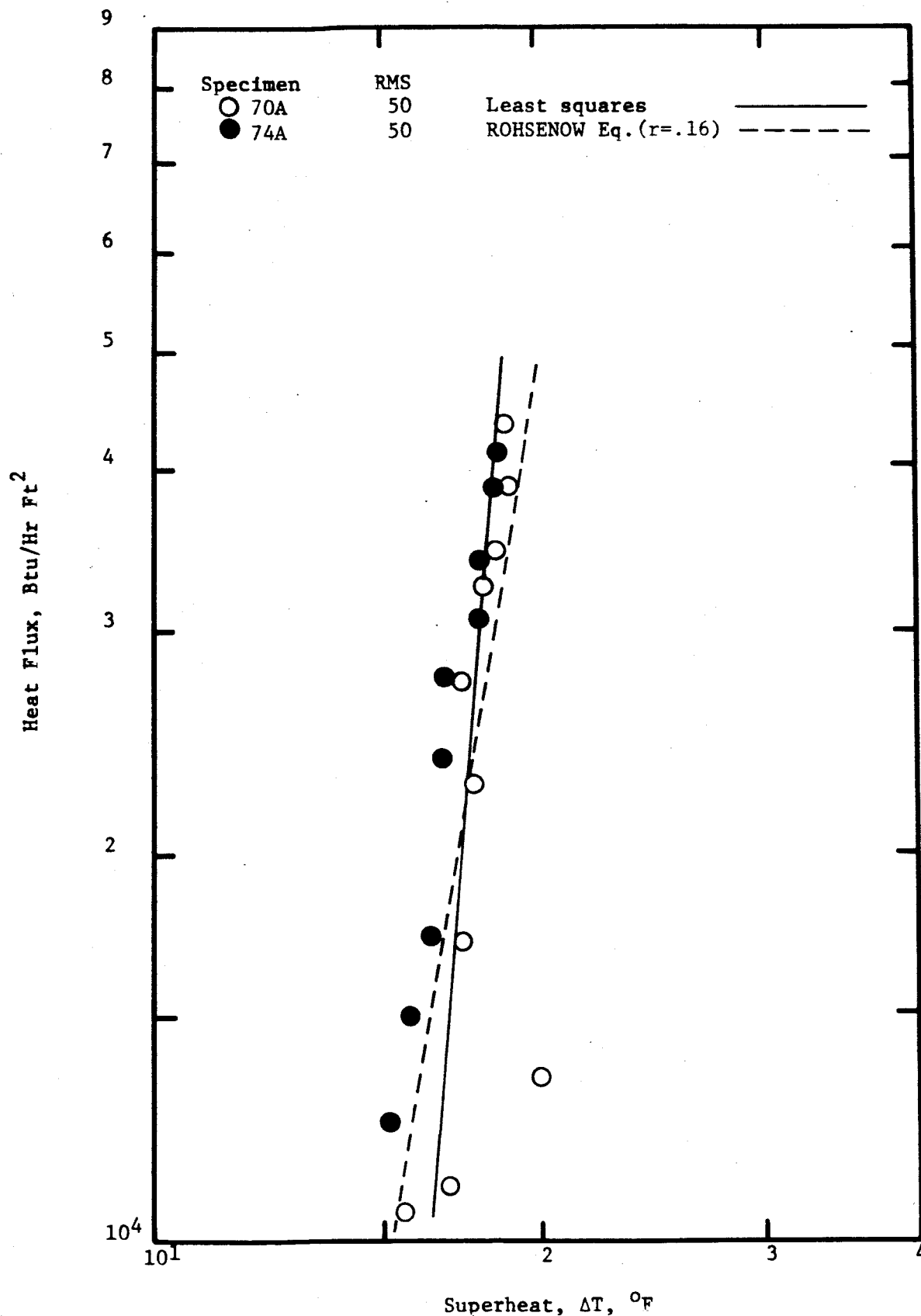


Fig. 11 Heat Flux versus Superheat for Chemically Etched Surfaces of 50 RMS.

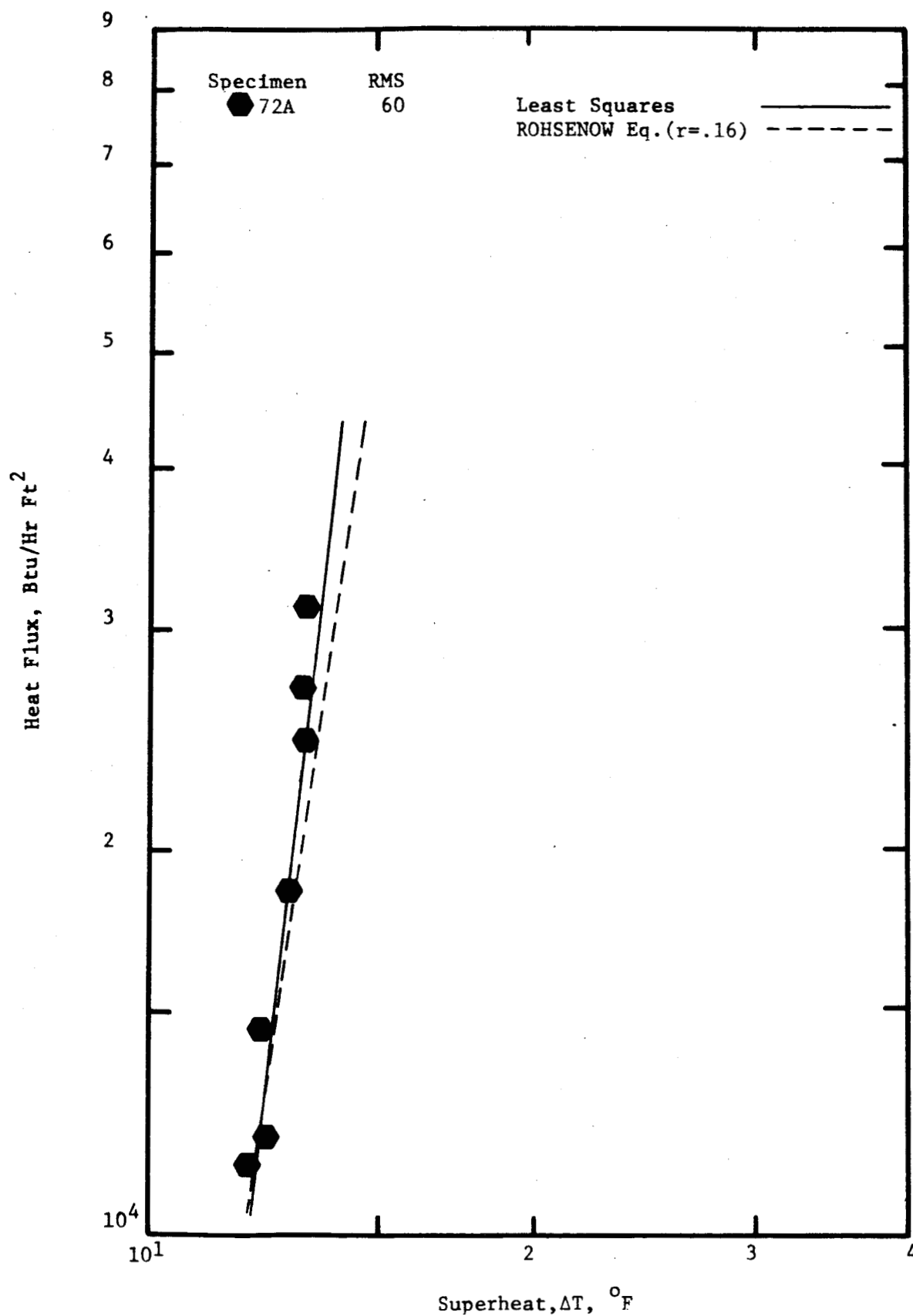


Fig. 12 Heat Flux versus Superheat for Chemically Etched Surfaces of 60 RMS.

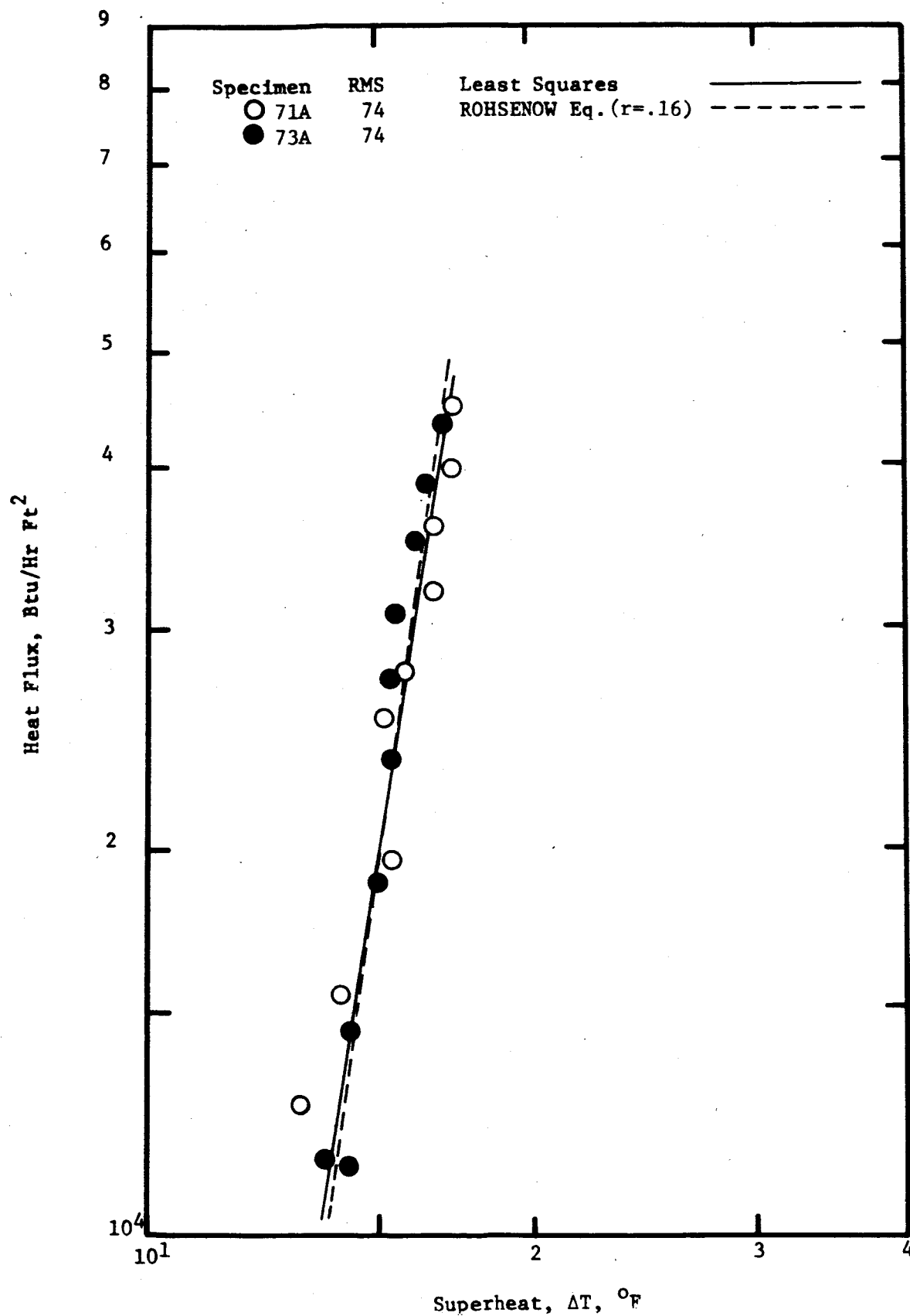


Fig. 13 Heat Flux versus Superheat for Chemically Etched Surfaces of 74 RMS.

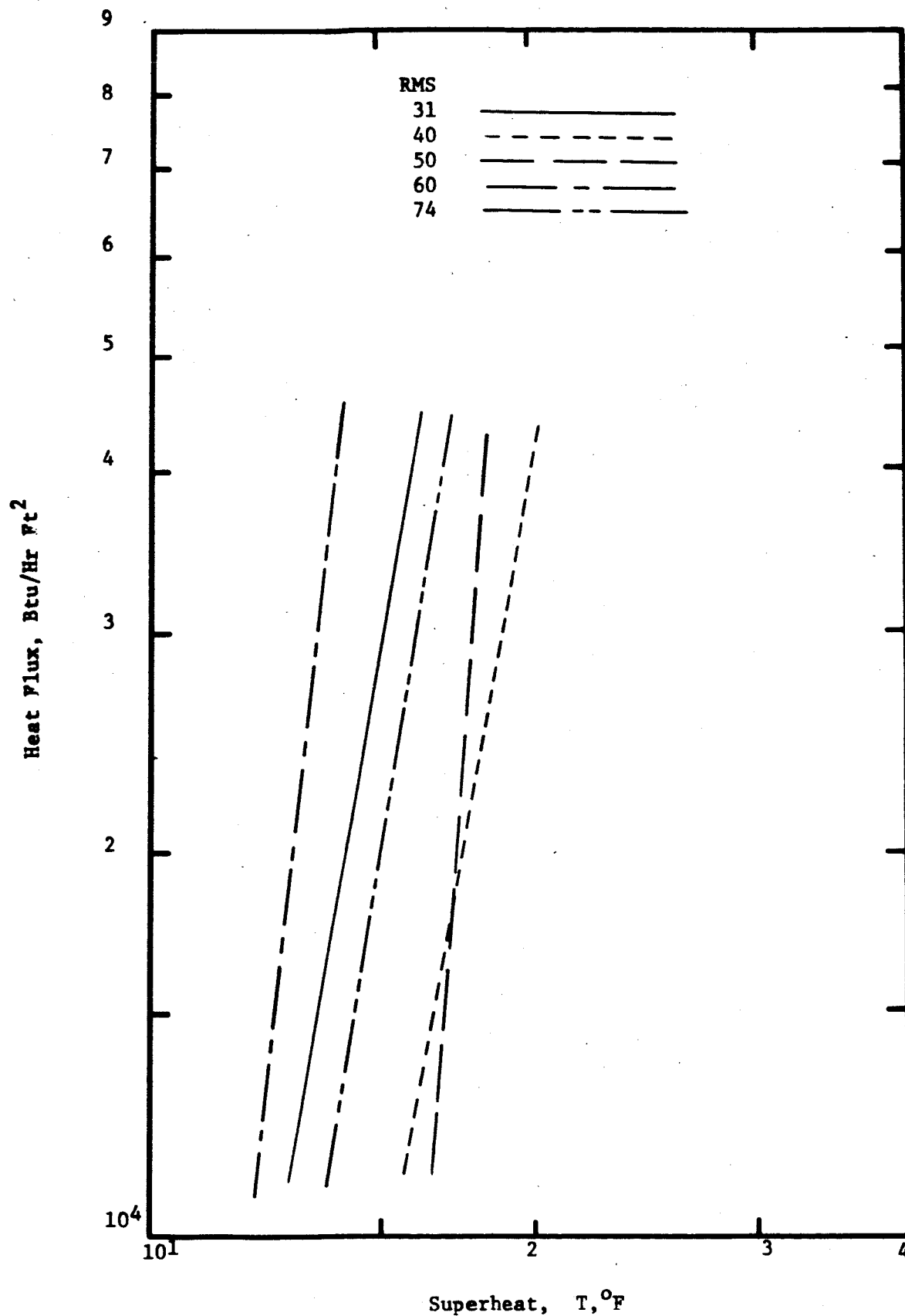


Fig. 14 Composite Heat Flux versus Superheat for Chemically Etched Surfaces.

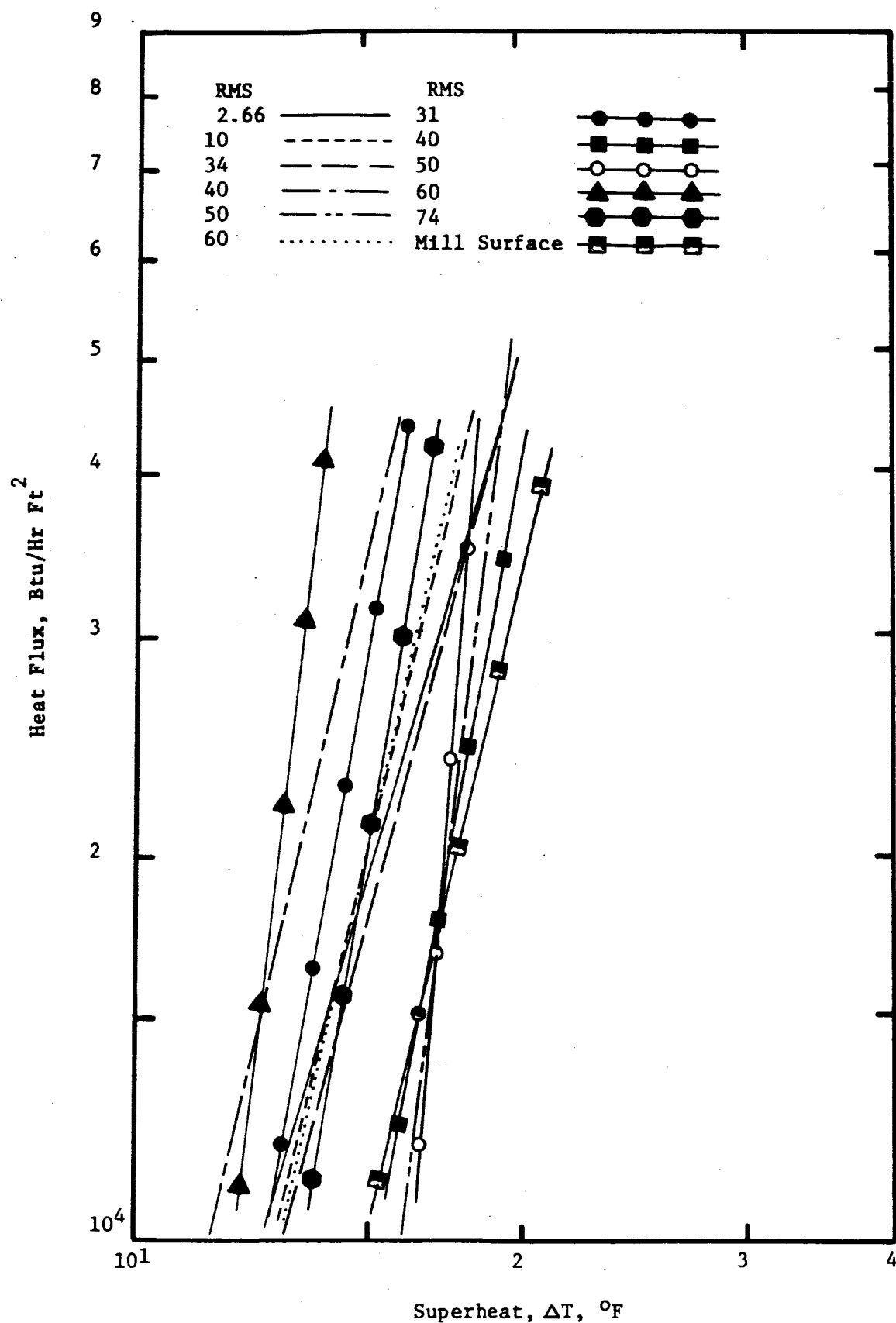


Fig. 15 Composite of Least Squares Fits for Mechanically Polished and Chemically Etched Surfaces.

TABLE I
RMS Values for Mechanically Polished Surfaces

Specimen Number	RMS		Grit	RMS Group
	Transverse	Lengthwise		
30	2.21	0.91	600	2.66
31	2.83	1.25	600	2.66
32	2.96	1.50	600	2.66
33	10.17	2.53	320	10
34	9.47	1.80	320	10
35	11.00	2.00	320	10
36	40.50	6.10	80	40
37	41.33	5.77	80	40
38	61.83	6.33	36	60
39	61.00	6.20	36	60
40	34.00	5.03	80	34
41	33.33	6.50	80	34
42	10.60	1.98	320	10
43	50.00	6.50	36	50
44	61.83	6.16	36	60
45	52.33	6.83	36	50
46	60.00	7.56	36	60

TABLE II

RMS Values for Chemically Etched Surfaces

Specimen Number	RMS Transverse Lengthwise		Preparation	RMS Group
70	50.0		Concentrated HCl (A.C.S. specifications) 5 hr	50
71	72.0	63.0	50% H ₂ O and 50% FeCl ₃ by wt. 2 hr 40 min	74
72	60.3	62.3	56 gm. CuCl ₂ . 350 ml HCl, and 200 ml H ₂ O 23 hr	60
73	76.0	76.0	50% H ₂ O and 50% FeCl ₃ by wt. 4 hr	74
74	50.0	50.0	50% H ₂ O and 50% FeCl ₃ by wt. 4 hr	50
75	38.0	41.0	50% H ₂ O and 50% FeCl ₃ by wt. 3 hr 30 min	40
76	31.5	32.0	Concentrated HCl (A.C.S. specifications) 6 hr	31

TABLE III

Values of Coefficient C_{sf} and Exponent r in Rohsenow Equation
for Mechanically Polished and Chemically Etched Surfaces

Mechanically Polished Surfaces

RMS	C_{sf}	r
2.66	.00897	.33
10	.00816	.33
34	.00875	.33
40	.00741	.33
50	.00968	.33
61	.00821	.33

Chemically Etched Surfaces

RMS	C_{sf}	r
31	.00643	.16
40	.00802	.16
50	.00774	.16
60	.00592	.16
74	.00683	.16

TABLE IV

Comparison of Exponent, r , in Rohsenow Equation for Boiling Studies

Reference	Surface-Liquid Combination	Surface Characterization	r	Q/A range
Gaertner & Westwater (6)	Copper-Nickel salt solution	Flat horizontal surface	.154	30,000 - 317,000
Griffith & Wallis (7)	Paraffin treated copper surfaces finished with 3/0 emery-water.	The surface had 37 holes of uniform size and shape evenly spaced on the surface.	.174	30,000 - 112,000
	Paraffin treated copper surfaces finished with 3/0 emery-water.	No cavities on the surface.	.148	14,000 - 300,000
Berenson (8)	Copper-pentane	Lap E	.246	10,000 - 80,000
	Copper-pentane	Emery 60	.303	7,000 - 90,000
	Copper-pentane	Emery 320	.264	4,000 - 100,000
	Copper-pentane	Mirror finish	.477	4,000 - 70,000
	Inconell-pentane	Lap E	.296	7,000 - 80,000
	Inconell-pentane	Mirror finish	.286	6,000 - 70,000
	Nickel-pentane	Lap E	.193	7,500 - 70,000
	Nickel-pentane	Mirror finish	.358	7,000 - 90,000
	Copper-pentane	Lap E in one direction	.236	4,500 - 90,000
	Copper-pentane	Lap E - Circular	.238	4,000 - 100,000
Hsu-Schmidt (9)	Stainless steel-water	140 rms	.25	10,000 - 100,000
	Stainless steel-water	21 rms	.286	10,000 - 40,000
	Stainless steel-water	19 rms	.308	10,000 - 40,000
	Aluminum-water	13 rms	.358	10,000 - 32,000
	Stainless steel-water	5.2 rms	.334	10,000 - 32,000